Air Dispersion Modeling 101: An Overview

Presented to

Arizona Air Toxics Stakeholders

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Objectives

- Introduce basic principles of air dispersion & modeling
- Describe commonly used air dispersion models
- Describe typical regulatory applications of air dispersion models

Model Applications

- Why model?
- Two ways to assess pollutant impacts
  - Measure
  - Estimate
- Measurement involves
  - Sampling (discrete / integrated)
  - Monitoring (continuous)

Model Applications – Why model?

- Measurement
  - Provides tangible results specific to a point or area
  - Methods typically geared to sensitivity
  - Quality is directly addressed
- Measurement has disadvantages
  - Costs (equipment, labs, personnel)
  - Availability of appropriate methods
  - Limited spatial / temporal coverage
  - Can only address existing sources

Model Applications – Why model?

- Modeling
  - Providing estimates over broad areas
  - Methods designed to be representative
  - Regulatory methods tend to be conservative
  - Quality is indirectly addressed
- Modeling weaknesses
  - Must rely on approximations
  - Can not account for every phenomenon

Model Applications – Why model?

- Modeling makes up for some measurement weaknesses
  - Lower costs (computers, personnel)
  - Applicable to numerous pollutants
  - Spatial / temporal coverage is greater
  - Applicable to existing or future sources

Model Applications

- Modeling is widely used in research and regulatory environments
- Regulatory applications focus on standardization and conservatism
  - Ensure that sources are treated consistently
  - Tend to overestimate impacts
- Research improvements filter down to regulatory applications

Model Applications - Examples

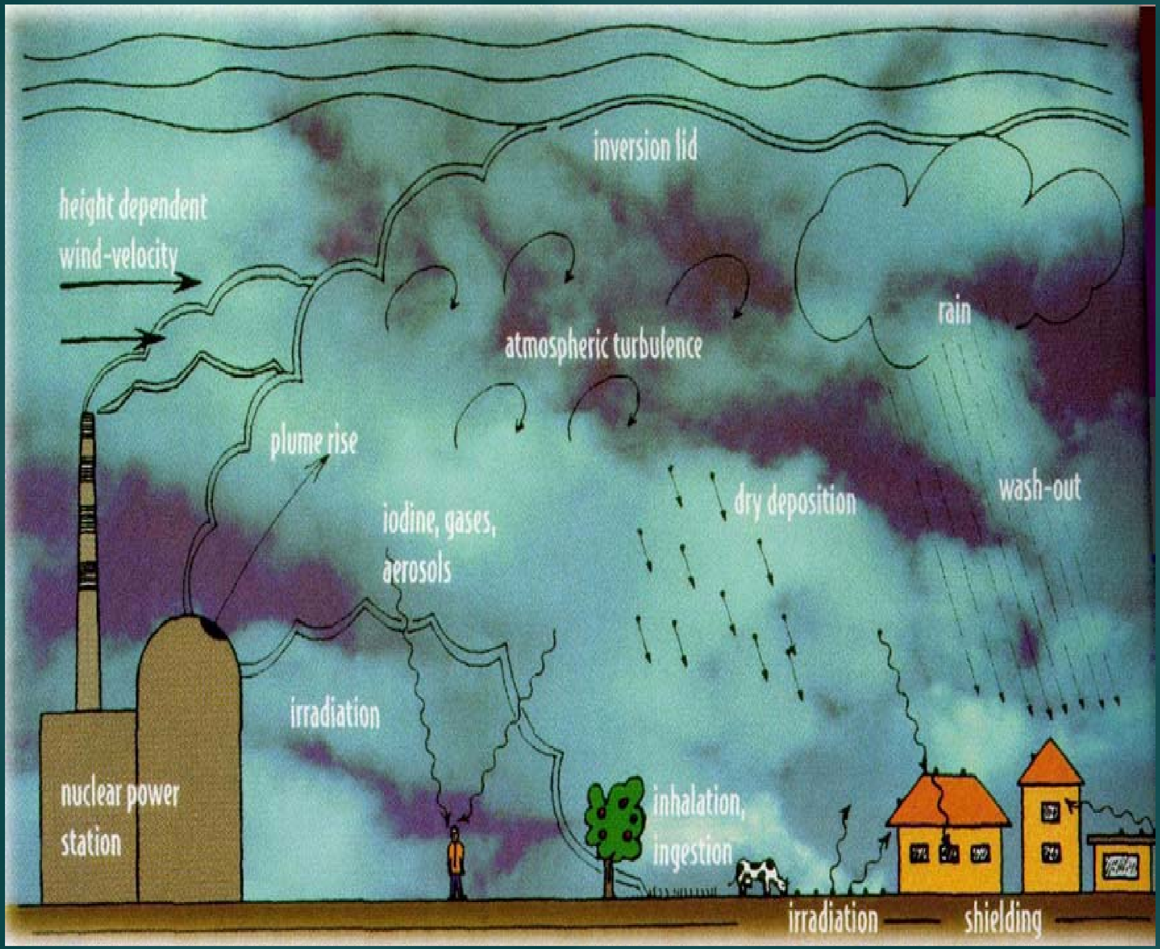
- Demonstrate compliance with CAA standards for permitting
  - National Ambient Air Quality Standards (NAAQS)
  - Prevention of Significant Deterioration (PSD) Increments
  - Class I Area Visibility & Deposition
- Demonstrate compliance with State air toxics regulations
- Provide input for Risk Assessments
  - Human health
  - Ecological

Air Dispersion - General

- In a broad sense, includes all processes that distribute emissions in the atmosphere
- Air dispersion processes are affected by
  - Atmospheric conditions
  - Emission source characteristics
  - Geographical settings
- Primary processes include transport, diffusion, and deposition

Air Dispersion - General

- An illustration of aspects of dispersion



(From: European Commission - Safeguarding Europe's Citizens).

Air Dispersion Modeling

- Modeling seeks to:
  - Estimate air concentrations
  - At specific locations (receptors)
  - For specific time (averaging) periods
- Models can be:
  - Physical
  - Numerical
  - Mathematical

Air Dispersion Modeling - Types

- Physical models:
  - Scale models of specific scenarios
  - Wind tunnels simulate atmosphere
  - Used for special cases of interest
- Numerical models:
  - Use complex 3D physics (fluid dynamics)
  - Need computing power
  - Simulate large 3D regions simultaneously
- These models are not typically used due to the high level of effort/cost involved

Air Dispersion Modeling - Types

- Mathematical models:
  - Simplify physics to varying degrees
  - Focus on pollutant plumes
  - Use more readily available inputs
- Mathematical models are the most frequently used models for regulatory applications
- Main models currently in use are based on the mathematical model known as the *Gaussian* model

Air Dispersion Modeling - Types

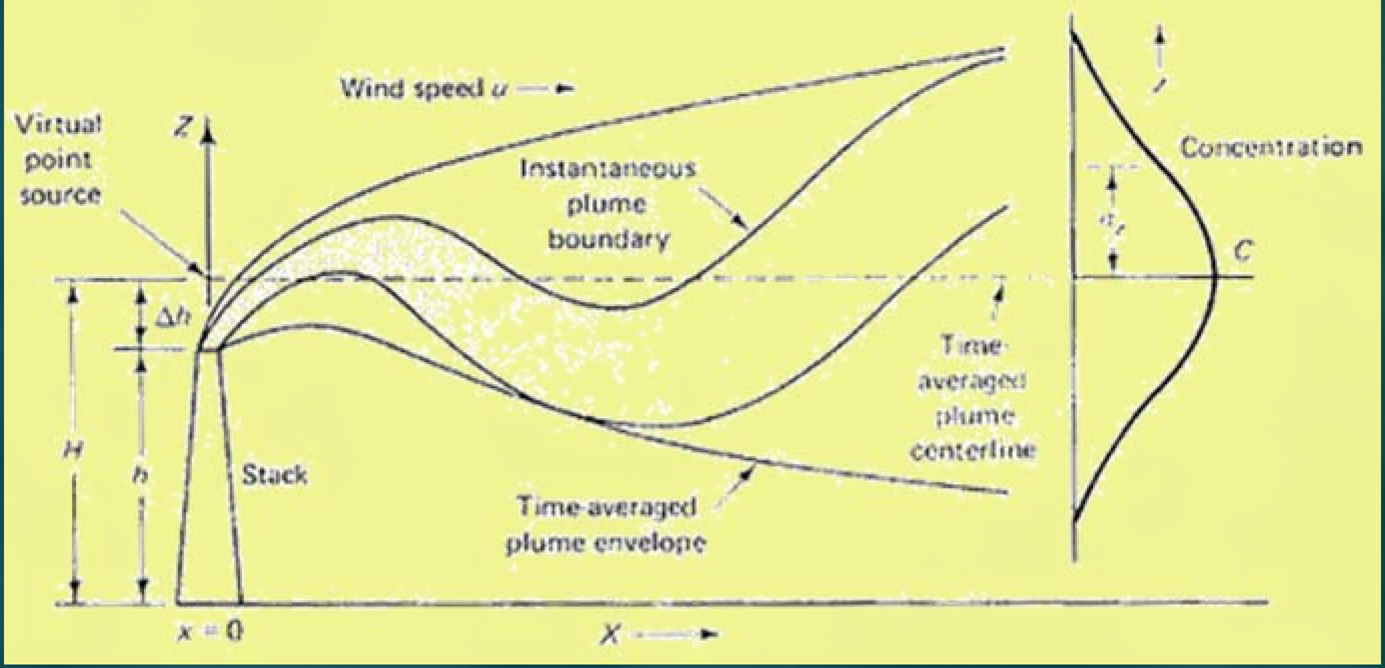
- Gaussian dispersion is used in air quality models in two ways:
  - Plumes
  - Puffs
- Plume models
  - Plumes built as fully-developed snapshots in time
  - Concentrations Gaussian about plume centerline
  - Plumes do not persist
- Puff models
  - Plumes built by continuous series of globular puffs
  - Concentrations Gaussian about puff centers
  - Puffs persist

Air Dispersion Modeling - Types

- Main regulatory models are based on the Gaussian plume concept
  - Underlying principles are the same
  - Models differ primarily in handling of specific aspects of dispersion
- Choice of plume vs puff based primarily on transport distance
  - Plume models used for short-range transport (distances of ~ 10 km or 6 mi)
  - Puff models used for longer ranges

Gaussian Models

- Gaussian models rely on observation that over time, concentrations in a plume tend to average into bell-shaped curves horizontally & vertically

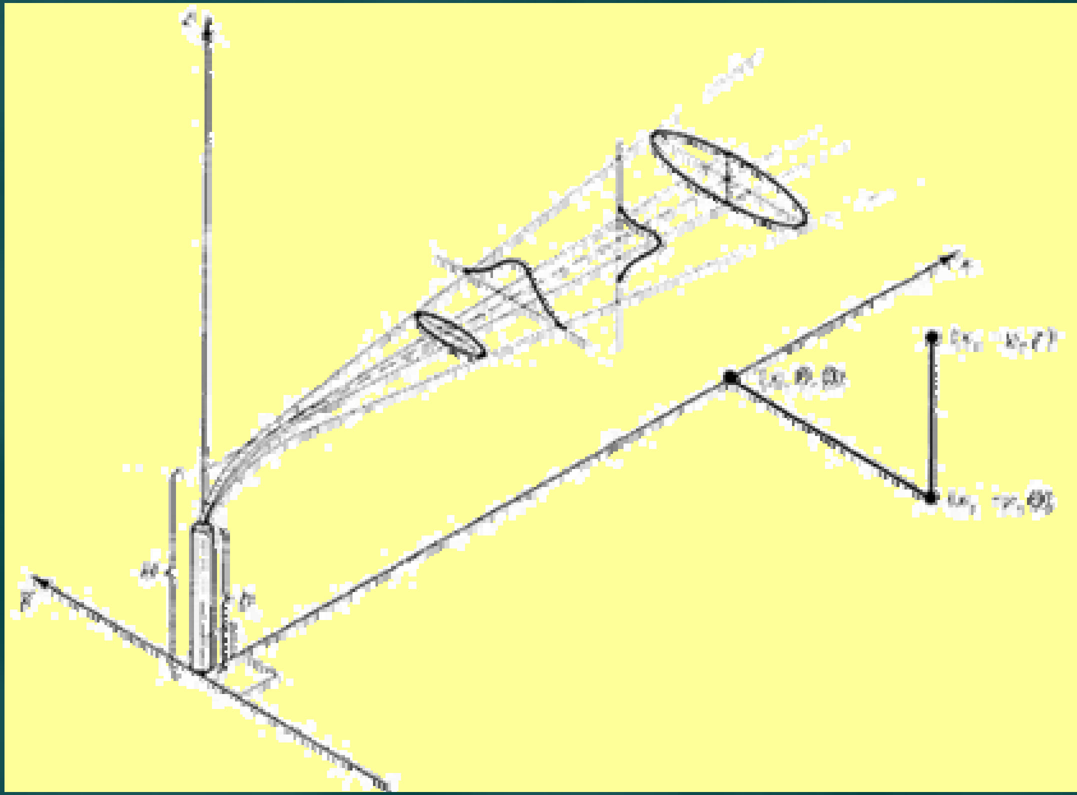


Gaussian Model

- Gaussian curve is familiar normal curve
  - Spread defined by standard deviation (σ)
  - Almost all pollutant mass is contained within ~2σ of centerline
- Mathematical plume is outlined by ellipses
  - Vertical axis $\propto$ σ_z (sigma-z)
  - Horizontal axis $\propto$ σ_y (sigma-y)

Air Dispersion

Perspective view of Gaussian plume shape



Gaussian Models

- Gaussian equations will describe the plume, once its dimensions and location are known
- So….. *Where's the plume??*
  - Height above ground?
  - Orientation?
  - Dimensions?
- Answers are defined by
  - Source characteristics
  - Atmospheric conditions
  - Geographic setting

Source Characteristics

- All source types share 2 primary characteristics for modeling:
  - Release height (above ground)
  - Release rate (generally mass / time)
- Other characteristics are specific to source types
- Emission source types
  - Point (stacks)
  - Volume (buildings, dumping, vehicle-raised dust)
  - Area (lagoons, storage piles)

Source Characteristics – By Type

- Point sources:
  - Gas exit temperature & velocity
  - Stack diameter
- Volume sources:
  - Initial horizontal & vertical dimensions
- Area sources:
  - Length & width
  - Orientation angle
  - Emissions = mass / area / time

Source Characteristics – Plumes

- Plumes rise from the stack to a final height at some distance downwind
  - Most of the plume is at final height
  - Adjustments are typically applied over the distance from the stack to the final rise
- Plume rise to final height is
  - Proportional to stack gas temperature & velocity (buoyancy & momentum)
  - Affected by atmospheric stability, wind speed & temperature

Atmospheric Conditions

- Main drivers of dispersion:
  - Stability
  - Wind speed & direction
  - Mixing depth
- Stability relates to the amount of turbulence
- Wind determines the transport of pollutants
- Mixing depth confines pollutants (limits dispersion)

Atmospheric Conditions - Stability

- Turbulence is generated by
  - Heating (thermal turbulence)
  - Obstacles to flow (mechanical turbulence)
- Stability reflects the atmosphere's ability to resist turbulence
  - Greater Stability = Less Turbulence
- Dispersion modeling views stability 2 ways (as convenient):
  - As discrete categories
  - On a continuous scale

Atmospheric Conditions - Stability

- Discrete stability categories
  - Developed based on observation & field experiments (Pasquill)
  - 6 categories, A-F
  - Used in many dispersion models

Category	Description
A	Very Unstable
B	Moderately unstable
C	Slightly unstable
D	Neutral
E	Slightly stable
F	Moderately stable

Atmospheric Conditions - Stability

- Categories can be related to general weather conditions
  – Used for incident modeling where limited data available
  – Many models use this basic approach

Wind Speed (m/s)	**Day**			**Night**	
	Incoming Solar radiation			Cloud Cover	
	Strong	Moderate	Slight	Mostly Cloudy/ Thin Overcast	Partly Cloudy
< 2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

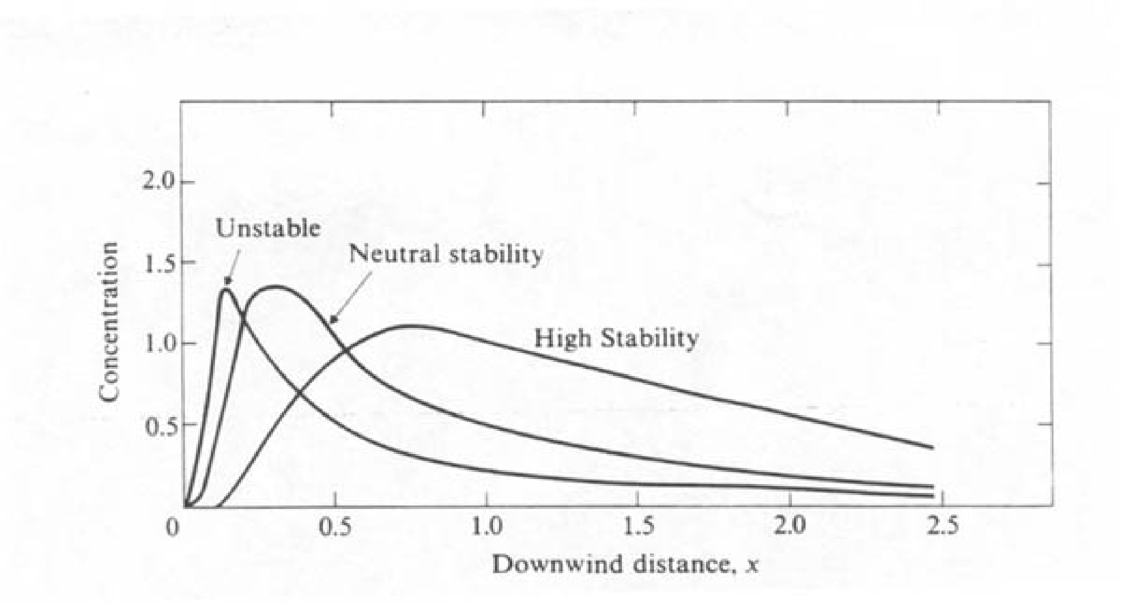
Atmospheric Conditions - Stability

- Continuous stability scale
  - Monin-Obukhov length (L)
  - Ratio of mechanical and thermal energy fluxes (turbulence)
  - Stable, L > 0; Unstable, L < 0
- Can be used to characterize other atmospheric parameters
- Table: example vs Pasquill categories (for flat rural roughness)

Category	1/L (m^{-1})
A	-0.125
B	-0.062
C	-0.020
D	0
E	0.022
F	0.072

Atmospheric Conditions - Stability

- Stability controls plume shape in Gaussian model
  - Plume σ's change with downwind distance is a function of stability
  - Downwind spread also governed by stability



Atmospheric Conditions - Winds

- Wind speed
  - Determines travel time
  - Concentration inversely proportional to speed in Gaussian model
- Wind direction
  - Determines transport direction
  - Plume centerline = mean wind direction
- Steady-state assumption
  - Each hour is a ‘snapshot’ in time
  - Model assumes plumes fully formed
  - Old plumes are forgotten in favor of new ones

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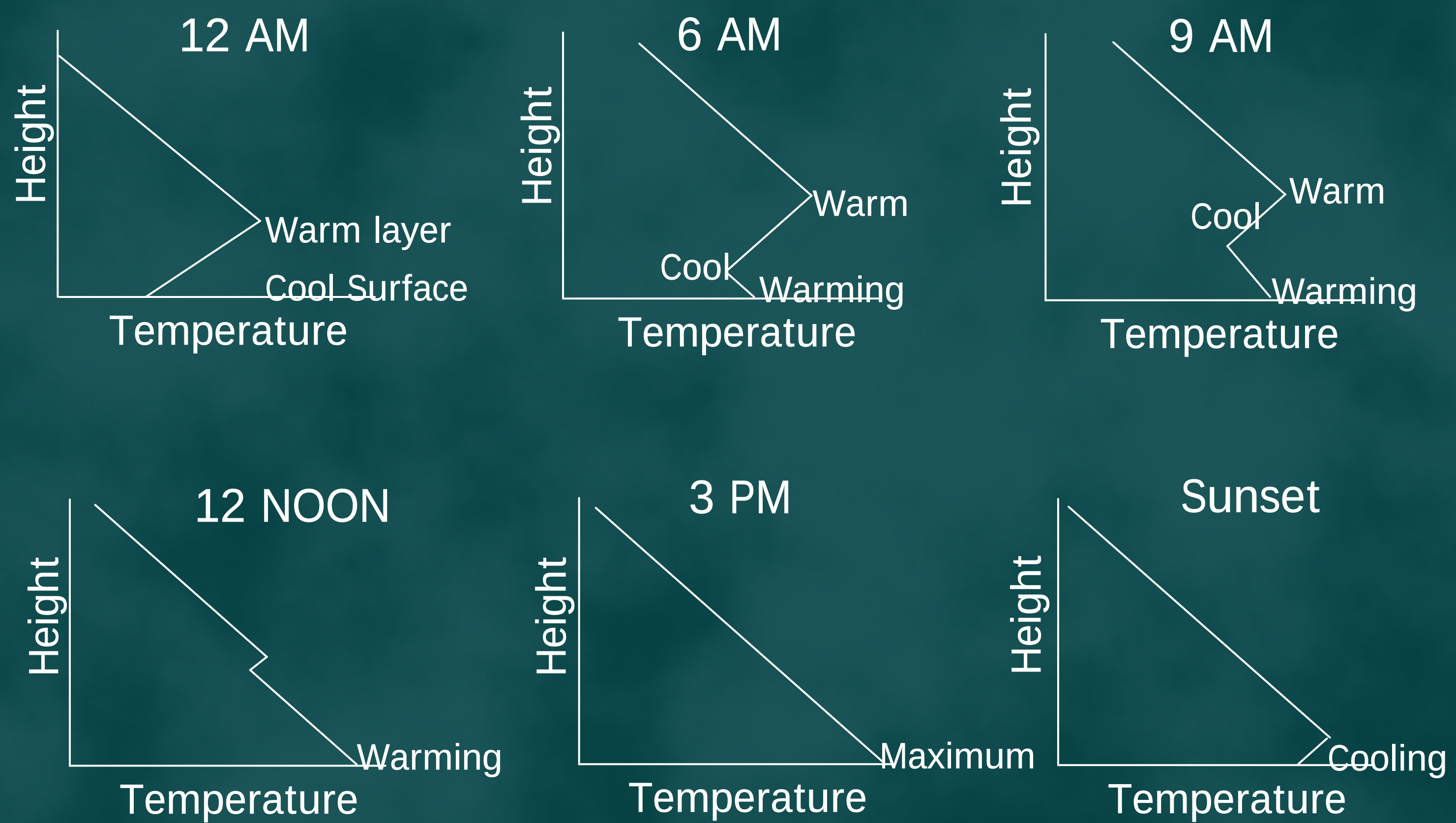
Atmospheric Conditions – Mixing Depth

- Mixing depth is the height of the layer in which dispersion will occur
  - Puts a "lid" on dispersion
  - Typically varies from 100 - 2000 m (300 – 6500 ft)
  - Higher or lower values may occur in specific conditions
- Strongly influenced by temperature profile
  - Inversions are often limiting factor
  - With no inversions, mixing can occur through entire boundary layer
  - Follows a diurnal cycle

Atmospheric Conditions – Mixing Depth

- Illustration of diurnal inversion cycle



Atmospheric Conditions – Mixing Depth

- Plumes can be trapped by the top of the mixed layer
  - Pollutants reflected back toward the ground
  - Generally increases concentrations
- Plumes can be isolated above the mixed layer
  - Pollutants not transported downward
  - No impacts below boundary
- Plumes can be split by the mixing boundary
  - Mixed effects
- Models can account for these effects

Geographic Setting

- Geographic setting of a source influences dispersion through
  - Land use around the facility
  - Surrounding buildings
  - Varying terrain elevations

Geographic Setting – Land Use

- Land use affects turbulence
  - Urban/populated areas are rougher than rural areas, disrupting air flow more
  - Results in different σ curves for rural & urban areas
  - Newer models account for land use by compass sector in meteorology preprocessing
- Rural & urban have specific meanings in regulatory modeling
  - Under EPA guidance, a majority of the area within 3 km of a source must have densely populated or industrial land uses to be considered "urban"
  - As a result, urban classification is seldom used

Geographic Setting – Buildings

- Buildings disrupt airflow around them
  - Creates a zone of disturbed flow
- Plumes may interact with the disturbed flow
  - Plume material may be drawn downward
  - Effect is referred to as “downwash”
- Downwash results in increased ground-level concentrations close to the stack source
  - Non-stack sources are not subject to downwash in models

Building Downwash

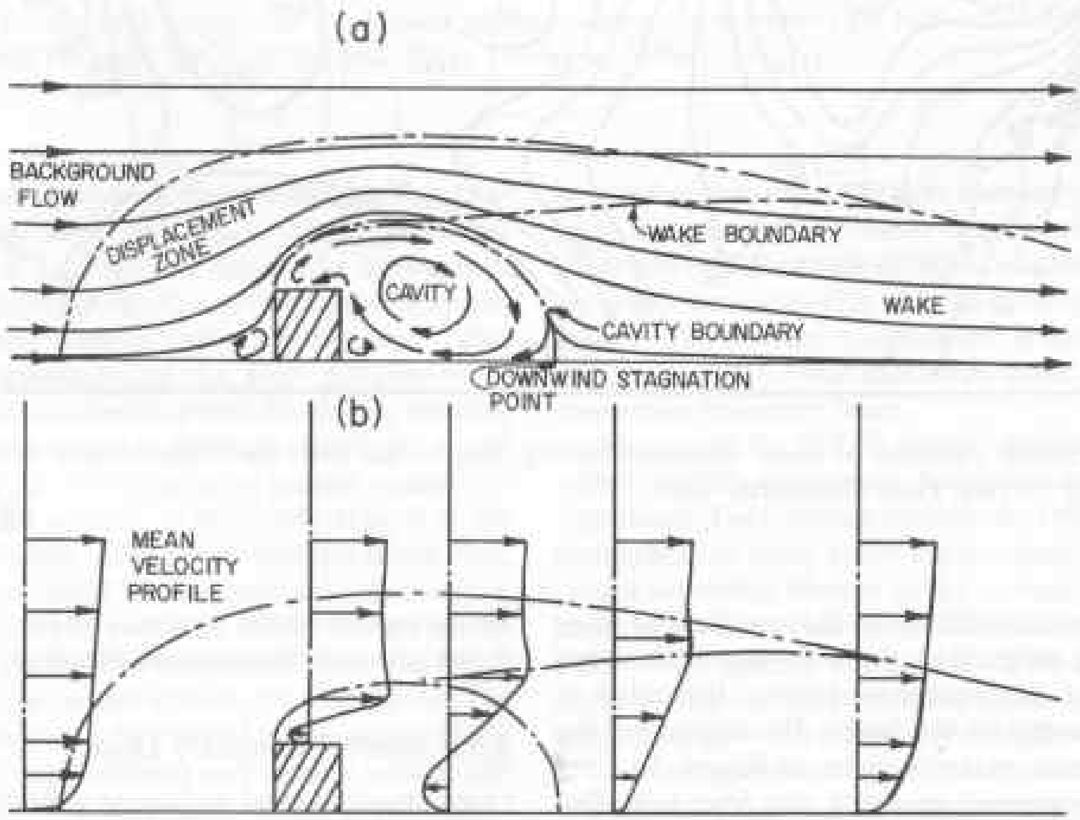


Figure 3.15 Schematic of the various flow regions around a two-dimensional wall or a building: (a) Mean streamline pattern. (b) Mean velocity profiles at various locations along the flow. From Halitsky, 1968.

Building Downwash

- EPA has defined "Good Engineering Practice" (GEP) stack heights to evaluate downwash effects
  - GEP height (H_{gep}) is the height above which downwash effects are avoided
  - For most cases, $H_{gep} = H_b + 1.5 * L_b$, where H_b is the height of the building and L_b is the lesser of the controlling building's height or maximum profile width
  - The controlling building is the building with the maximum H_{gep} for a stack.
  - A building is eligible to be the controlling building if any corner of the building is within $5 * L_b$ of the stack.

Building Downwash

- GEP height example:
  - 100 ft long, 60 ft wide, 24 ft tall building
  - $H_b = 24$, $L_b = 24$
  - $H_{gep} = 2.5 * 24 = 60$ ft
  - Stack tops 60 ft or higher above ground (36 ft above roof top) will not suffer downwash effects
  - Stack tops shorter than 60 ft will be subject to downwash effects

Building Downwash

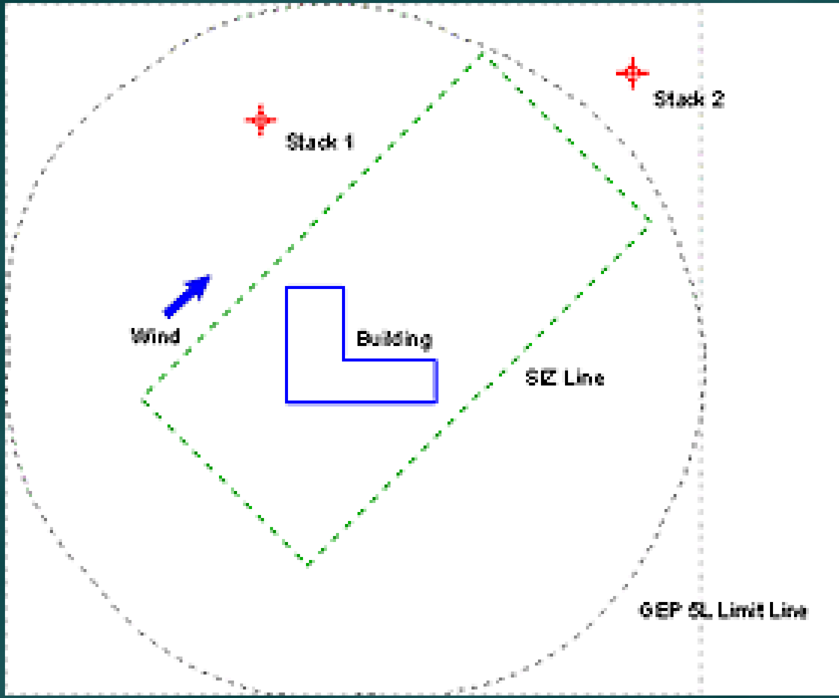
- Regulatory models contain algorithms to account for downwash effects
  - Downwash can increase concentrations by factors of 2-5 times
  - More sophisticated algorithms being incorporated into some regulatory models
- Refined models handling downwash need detailed information
  - Scaled map of building outlines, including tiers (corner coordinates)
  - Heights of all tiers
  - Coordinates of all stacks

Building Downwash

- Separate program used to develop downwash-related inputs to dispersion model
  - Influence zones change with wind direction
  - Influence zones from multiple tiers need to be compared
  - Controlling building tiers can change w/ wind direction
  - Newer algorithms need more direction-specific information

Building Downwash

- Illustration of building downwash effects zones



Geographic Setting – Terrain

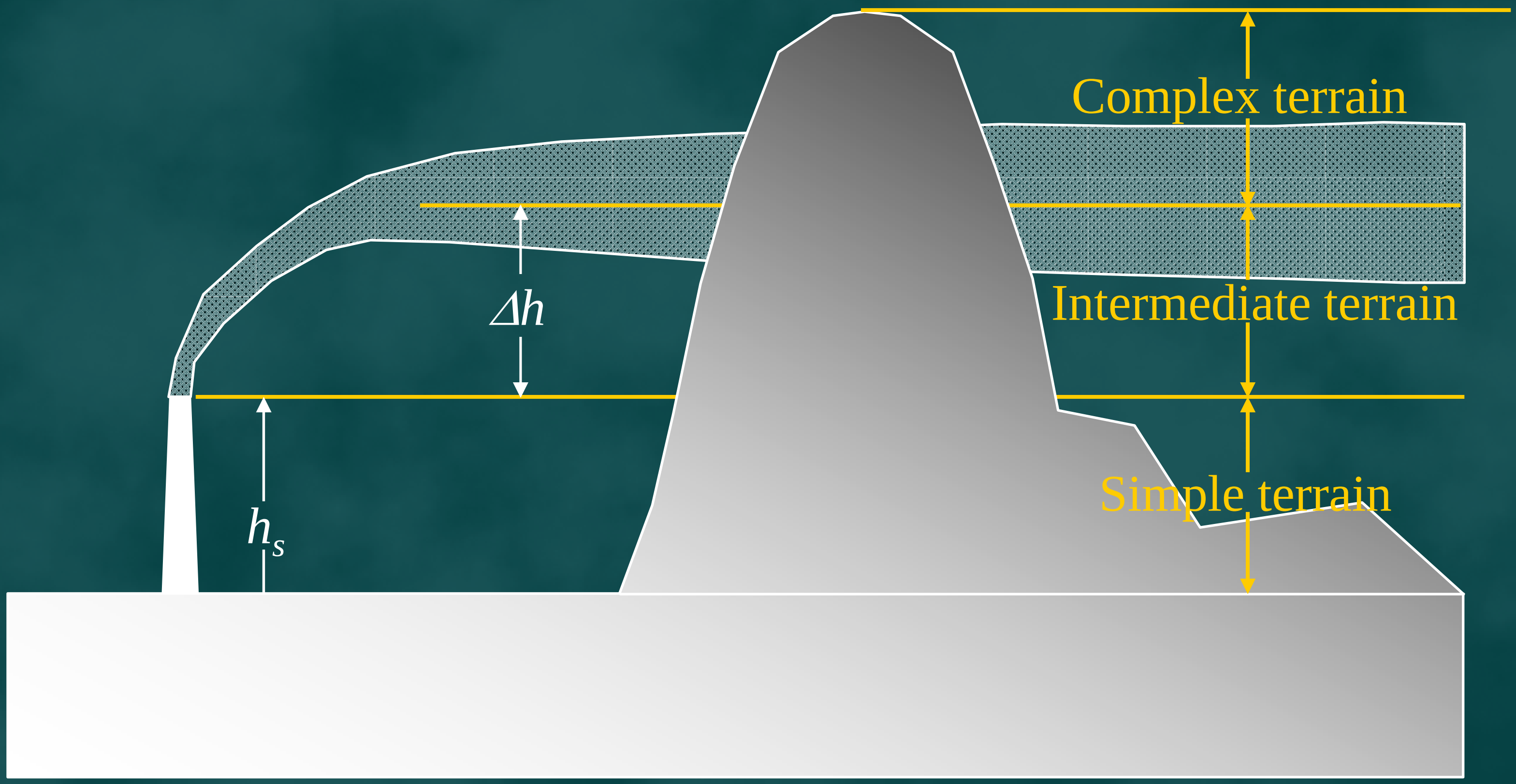
- Real-world terrain alters the path of air flow and plumes
- Receptors are placed in networks that overlay the terrain
  - Receptor location elevations are inputs to models
  - Elevation data are obtained from USGS Digital Elevation data sets
- Elevation affects concentration by its placement relative to the plume centerline

Geographic Setting – Terrain

- Gaussian plume models see terrain in 3 general categories
  - *Simple* terrain – elevations below stack top
  - *Complex* terrain – elevations above final plume height
  - *Intermediate* terrain – range of elevations between simple and complex levels
- Models compensate to account for terrain types

Geographic Setting – Terrain

- Terrain classifications



Geographic Setting – Terrain

- Gaussian plume models generally limited in treatment of terrain effects on plumes
  - Basic model treats plume as shown on previous slide
  - Steady state plume models do not generally account for local air flow around terrain features
- Regulatory plume models vary in treatment of complex terrain
  - Some provide adjustments for plume impaction on hillsides
  - Some include algorithms to decide if plume hits, rides over or goes around hills (critical dividing streamline)
  - Some models are specifically designed to evaluate complex terrain features

Dispersion Models

- Focus on the primary USEPA regulatory models
  - Models & information can be found on EPA Support Center for Regulatory Air Modeling (SCRAM)
    - Online at www.epa.gov/ttn/scram/
  - Other models are included on the site
- There are 4 models frequently encountered in permitting situations

Dispersion Models

- SCREEN3
- ISC3
  - Industrial Source Complex, Version 3
- CTDMPLUS / CTSCREEN
  - Complex Terrain Dispersion Model
  - PLus Algorithms for Unstable Situations
- CALPUFF
  - CALifornia Air Resources Board PUFF Model

Dispersion Models – SCREEN3

- SCREEN3 is a screening version of the full ISC3 model
  - Screening is used to determine whether more refined modeling is needed
  - If screening concentrations are below required thresholds, refined modeling may not be necessary
- This model contains essentially the same core calculations as ISC3
  - Some simplifications due to the screening assumptions

Dispersion Models – SCREEN3

- Model features
  - Single source model
  - Point, area, and volume sources
  - Downwash effects
  - Synthetic meteorology matrix (no WD)
  - Simple & complex terrain
  - 1-hour averages only
  - Special calculations (not in ISC3)
    - Flare sources
    - Building wake cavity
    - Shoreline & inversion breakup fumigation

Dispersion Models – SCREEN3

- Synthetic meteorology matrix
  - 13 wind speeds (1 – 20 m/s or 2 – 45 mph)
  - 6 Pasquill stability classes
  - 54 combinations
    - High wind speeds not associated with very stable/unstable categories
  - Mixing heights proportional to wind speed
  - All 54 combinations are evaluated
  - Worst-case concentrations are output
- User converts 1-hour averages to longer periods using predefined scaling factors

Dispersion Models – SCREEN3

- No wind direction
  - Receptors on plume centerline only
  - Automated or user-chosen distances
  - Mixing heights proportional to wind speed
- Cavity calculations
  - Winds along maximum building length & width used (2 calculations)
  - Estimate length & maximum concentration for each building cavity zone

Dispersion Models – ISC3

- The “workhorse” air dispersion model
- Full-featured, refined model allowing
  - Multiple sources
  - 3-D receptor distribution
  - Actual (representative) meteorological data

Dispersion Models – ISC3

- Model features
  - Used for all terrain areas (simple, intermediate, complex)
  - Point, volume, area, and pit sources
  - Wet & dry particle, dry gas deposition
  - Building downwash effects
  - Uses Pasquill stability
  - Rural or urban dispersion curves used for all wind directions
  - Single point, single level meteorological data
  - Multiple averaging periods

Dispersion Models – ISC3

- Intermediate terrain treatment
  - Algorithms for simple & complex terrain
  - Intermediate terrain model tries both, picks maximum
- Deposition estimates available
  - Gas deposition (dry only) needs deposition velocity
  - Particle deposition requires particle size distribution
  - Wet deposition requires precipitation data
  - Removal of material from plume is optional
- Concentrations at 1-hour intervals
  - Longer periods are block averaged
  - Includes EPA procedure for handling calm hours

Dispersion Models – CTDM

- CTDMPLUS & CTSCREEN are designed specifically for evaluating complex terrain features
  - Point sources only, no downwash
  - CTDMPLUS uses actual, multilevel meteorological data
  - CTSCREEN uses a screening approach to choose worst-case wind direction
- Both models look at specific terrain features (hills)
  - Actual hill elevation contours must be digitized as input
  - Receptors may be placed on contours or elsewhere on hills
- These models are only used where plume impacts on terrain features is of particular concern (ISC3)

Dispersion Models – CALPUFF

- CALPUFF is a Gaussian puff model
  - Sources release puffs at a rate according to wind speed
  - Puffs disperse as they are moved by wind field
  - Concentrations within puffs are Gaussian
  - Puffs from previous hours persist
  - Puffs are tracked over lifetime in model domain
- Used for long-range transport
  - Assumption of straight-line plumes not valid for long distances (> 10 km)
  - Puffs follow curving trajectories based on wind direction changes

Dispersion Models – CALPUFF

- Model features
  - Point, volume, area sources
  - Downwash effects
  - Chemical transformations (sulfate, nitrate, ammonia)
  - Multiple meteorological stations over large model domains
  - Multiple vertical layers
  - Gridded 3-D wind fields including terrain effects
  - Dry and wet deposition

Dispersion Models – CALPUFF

- Extremely sophisticated model
  - Requires significant effort
  - Model domains can cover 100 x 100 mile areas
- Extensive input data pre-processing requirements
  - Land use / land cover data
  - Terrain elevation data
  - Surface meteorological data
  - Upper air meteorological data
  - Preprocessors can take longer to run than the model itself!

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Dispersion Models – CALPUFF

- Fortunately, there is a screening mode
  - Model can be run with only ISC3 meteorological data (single-station, single-level)
  - CALPUFF uses same source inputs as ISC3
- Used for Class I area evaluations
  - Class I areas are natural parks, forests, and wildlife preserves specifically protected in the CAA
  - Visibility of natural vistas is primary concern
  - Sulfates, nitrates, ammonia, and fine particle pollution decrease ‘natural’ visibility
  - CALPUFF specifically designed to model these effects
  - Also provides acid deposition estimates for park ecosystems

Dispersion Models – AERMOD

- The ISC model has been in use for over a decade
  - Dispersion modeling research has advanced
- Quest for a successor to ISC3
- Began 1991 with AMS/EPA Regulatory Model Improvement Committee (AERMIC)
  - 1999 – AERMIC Model (AERMOD) released
  - 2000 – Formally proposed as regulatory model
  - 2003 – Latest round of public comment
  - 2005 – Latest Beta-test release
- AERMOD is generally considered on a case-by-case basis by agencies, pending final approval

Dispersion Models – AERMOD

- Model features
  - Same interface as ISC3
  - New meteorology & terrain preprocessors
  - Uses Monin-Obukhov stability
  - Uses vertical profiles of wind, temperature, and turbulence
  - All elevation ranges treated consistently
  - Land use incorporated by direction sector in profile calculations
  - Improved downwash treatment

Dispersion Models – AERMOD

- AERMOD relies on similarity theory
  - Parameters (wind, temperature, etc.) in boundary layer follow similar profiles with height (z)
  - Each can be expressed in terms of a scaling height (Monin-Obukhov Length)
  - Profiles calculated based on z/L

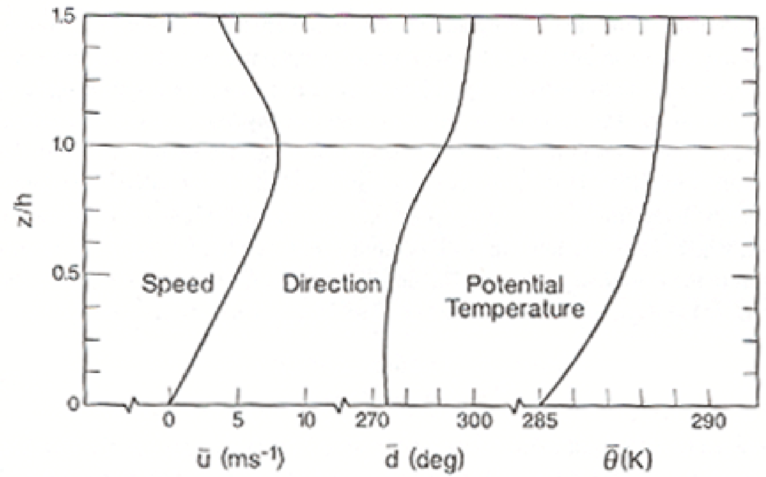

Fig. 1.2. Mean vertical profiles of wind speed, wind direction, and potential temperature in the stable boundary layer.

Dispersion Models – AERMOD

- Profile benefits
  - More realistic representation than fixed curves
  - Allows use of multi-level meteorological data
- AERMOD has evolved from original proposed version
  - Plume RIse Model Enhancements (PRIME) developed for ISC in 1998 are now in latest Beta (downwash effects)
  - Dry & wet deposition processes have been added